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RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

PERIODIC SINGLE-BLADE LOADS ON PROPELLERS
IN TANGENTIAL AND LONGITUDINAL WAKES

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DOCUMENT
COLLECTION

by

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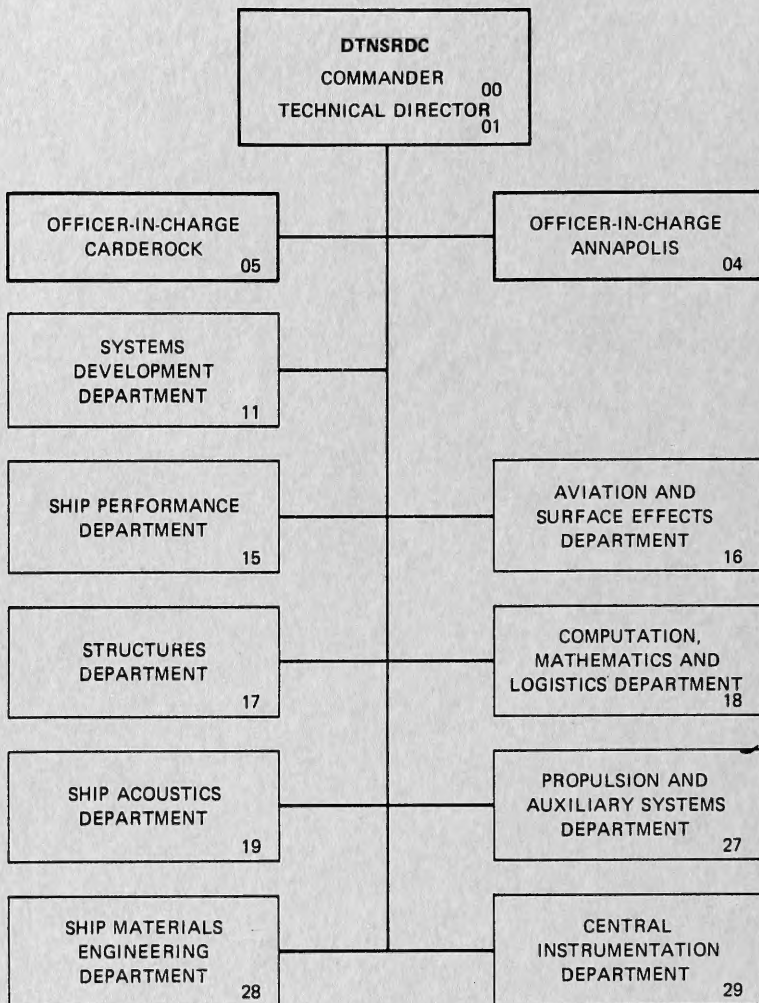RESEARCH AND DEVELOPMENT REPORT

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Periodic single-blade loads were measured on model propellers in in-
clined flow and in a single-cycle circumferentially non-uniform longitudinal
velocity field. The experimental results were correlated with predictions
by the following methods:

    1. A quasi-steady procedure developed by McCarthy at David W. Taylor
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       2. An unsteady lifting surface theory developed by Tsakonas and
           his colleagues at Davidson Laboratory,
       3. An unsteady lifting surface theory developed by Kerwin and Lee
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       4. A refinement by Kerwin to the method of Kerwin and Lee to
           consider the inclination of the propeller slipstream.

    In inclined flow, all four of the calculation methods evaluated
consistently underpredicted the experimental values of the periodic
single-blade loads. The method of Kerwin, which considers the in-
clination of the slipstream relative to the propeller axis, produced
the best correlation with experimental values. These correlations
show that the inclination of the propeller slipstream relative to the
propeller axis significantly influence the periodic single-blade loads.
The importance of this inclination increases with increasing time-
average loading.

    In longitudinal flow, all of the calculation procedures predicted
periodic single-blade axial force at design advance coefficient to
within 20 percent of the experimental values, but agreement was not as
good at off-design advance coefficients. The method of Kerwin and Lee
produced the best overall correlation with experimental results
considering both amplitude and phase of the periodic single-blade axial
force over a range of advance coefficients.

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ABSTRACT

Periodic single-blade loads were measured on model propellers in inclined flow and in a single-cycle circumferentially non-uniform longitudinal velocity field. The experimental results were correlated with predictions by the following methods:

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In longitudinal flow, all of the calculation procedures predicted periodic singleblade axial force at design advance coefficient to within 20 percent of the experimental values, but agreement was not as good at off-design advance coefficients. The method of Kerwin and Lee produced the best overall correlation with experimental results considering both amplitude and phase of the periodic single-blade axial force over a range of advance coefficients.

NOMENCLATURE

A_E	Expanded area, $Z \int_{r_h}^{R} c\,dr$
A_O	Propeller disk area, $\pi D^2/4$
c	Blade section chord length
D	Propeller diameter
$F_{x,y,z}$	Force components on blade in x,y,z directions
J	Advance coefficient, $J = V_A/nD$
K_Q	Torque coefficient, $Q/(\rho n^2 D^5)$
K_T	Thrust coefficient, $T/(\rho n^2 D^4)$
$M_{x,y,z}$	Moment components about x,y,z axes loading on one blade
n	Propeller revolutions per unit time
P	Propeller blade section pitch
Q	Time-average propeller torque arising from loading on all blades, $-Z\overline{M}_x$
R	Radius of propeller
r	Radial coordinate from propeller axis
T	Time-average thrust of propeller, positive forward, $Z\overline{F}_x$
V	Model speed
V_A	Propeller speed of advance
$V_r(r,\theta_w)$	Radial component of wake velocity, positive towards hub
$V_t(r,\theta_w)$	Tangential component of wake velocity, positive clockwise looking upstream for left-hand propeller, positive counter-clockwise looking upstream for right-hand propeller
$V_x(r,\theta_w)$	Longitudinal component of wake velocity, positive forward
V_{VM}	Volume mean longitudinal velocity through propeller disk determined from wake survey

1

w_{VM} Wake fraction determined from volume mean longitudinal velocity through propeller disk determined from a wake survey, $(V-V_{VM})/V$

x,y,z Coordinate axes

Z Number of blades

θ Angular coordinate used to define location of blade and variation of loads, from vertical upward, positive counterclockwise looking upstream for left-hand propeller, positive clockwise looking upstream for right-hand propeller, $\theta = -\theta_w$

θ_w Angular coordinate of wake velocity, from upward vertical, positive clockwise looking upstream for left-hand propeller, positive counterclockwise looking upstream for right-hand propeller, $\theta_w = -\theta$

$^K(F)_n$ nth harmonic force coefficient, $(F)_n/(\rho n V_A D^3)$

$^K(M)_n$ nth harmonic moment coefficient, $(M)_n/(\rho n V_A D^4)$

   Mass density of water

$(\phi_{F,M})_n$ nth harmonic phase angles of F,M based on a cosine series,

$$(F,M) = (\overline{F},\overline{M}) + \sum_{n=1}^{N} (F,M)_n \cdot \cos\{n\theta - (\phi_{F,M})_n\}$$

ψ Inclination of propeller shaft

Subscripts:

d   Value at the near design condition

EXP   Value of experimental measurements

h   Value of hub radius

n   Value of nth harmonic

REF   Value at specified reference advance coefficient

x,y,z Component in x,y,z direction

Superscripts:

—   Time-average value per revolution

INTRODUCTION

The once-per-revolution (or shaft frequency) propeller blade loads are important for consideration of propeller blade fatigue strength [1,2,3,4]. Therefore, an investigation was undertaken at DTNSRDC to evaluate the periodic blade loads on propellers in inclined flow and in circumferentially non-uniform longitudinal velocity fields.

Systematic experiments were conducted on three model propellers (see Table I) operating in inclined flows generated by shaft inclinations of 10, 20, and 30 degrees, and in a once-per-revolution circumferentially non-uniform longitudinal velocity field produced by an upstream wire-grid screen. The inclined flow produces a once-per-revolution variation of the tangential component of velocity in the propeller plane; therefore, the inclined flows are sometimes referred to as tangential wake patterns.

TABLE I – CHARACTERISTICS OF PROPELLERS
4661, 4710, AND 4402

PROPELLER NUMBER	4661	4710	4402
Diameter, D (feet)	0.6848	0.7273	0.7687
Rotation	Left Hand	Right Hand	Right Hand
Number of Blades, Z	5	4	5
Hub-Diameter Ratio, D_h/D	0.300	0.312	0.290
Expanded Area Ratio	0.730	0.775	0.830
Design Advance Coefficient	1.140	0.860	0.767
Pitch-Diameter Ratio (P/D) at r/R = 0.7	1.532	1.111	1.061

The experimental results were correlated with predictions by the following theoretical methods:

1.   A simple quasi-steady procedures developed by McCarthy [5] at DTNSRDC which utilizes the open
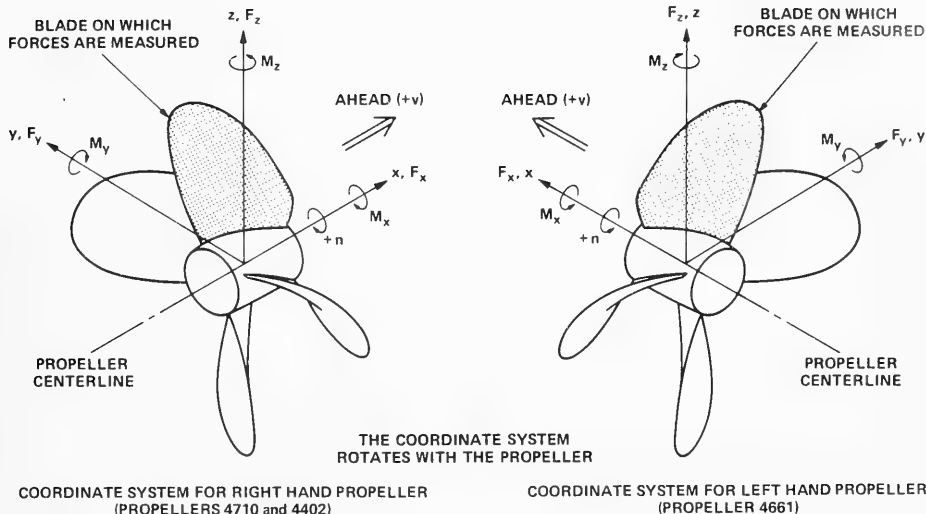
Fig. 1 — Components of Blade Loading

water characteristics of the pro-
peller,
2. A linearized lightly-loaded
unsteady lifting surface theory
developed by Tsakonas, et al (6,7)
at Davidson Laboratory,
3. A moderately-loaded unsteady
lifting surface theory developed by
Kerwin and Lee (8) at MIT,
4. A refinement by Kerwin (9) to the
method of Kerwin and Lee which
considers the inclination of the
propeller slipstream for opera-
tion in inclined flow.

BACKGROUND

In previous work unsteady loads
(see Figure 1) were measured on a single
blade of model propellers operating
behind model hulls with open-shaft
transom sterns (1,2,3,4). It was found
that for these vessels the unsteady
blade loads were produced primarily by
the tangential component of the wake
velocity; see Figure 2. For the steady
ahead conditions, the experimentally
obtained unsteady loads were correlated
with unsteady loads deduced from strains
measured on the respective full scale
propeller blades and with predictions
based on unsteady lifting surface theory
developed by Tsakonas, et al (6,7), and
the quasi-steady method of McCarthy (5).

For each of these propeller-hull
combinations, the circumferential

variation of loading determined from the
model experiments agreed fairly well
with full-scale data, but was substan-
tially larger than the predictions by
the two theoretical methods.

In an attempt to isolate the
reasons for the large discrepancy
between these experimental and
theoretical results, the following
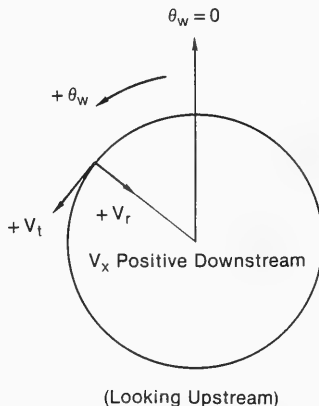experimental work on model propellers
was undertaken:

(Looking Upstream)

Fig. 2 — Sign Convention for Ship Wake
Velocity Components

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1. Measurement of the six components of blade loading under various idealized conditions including:
   a. In inclined flow without an upstream hull.
   b. In a once-per-revolution variation of longitudinal flow produced by an upstream wire-grid screen.
   c. Over a range of propeller advance coefficients.
   d. Over a range of clearances between the propeller tip and a flat plate above the propeller.
2. Measurement of the field point velocities induced by a propeller operating in inclined flow.
3. Measurement of the pressure distribution on the surfaces of the blades of two propellers operating in inclined flow.

This paper presents the results of the blade loading experiments under idealized conditions, and correlation with available theories including one which considers the influence of slipstream for operation in inclined flow. These results supercede the preliminary results presented in Reference 10. More details of these results will be presented in future DTNSRDC Reports. The field point velocity measurements were reported in Reference 11. The results of the blade surface pressure measurements will be presented in a future DTNSRDC Report.

EXPERIMENTAL TECHNIQUES

The experiments were conducted on DTNSRDC Carriage 2. The propellers were mounted at the front of the downstream drive system containing the dynamometer and the drive motor. This system was the same as that used in the experiments described in detail in References 2 and 3 except that the downstream body was modified so that it could be operated fully submerged. The modifications included a waterproof housing for the drive motor, waterproof electrical cables and connectors, removal of the upper apron which had extended the sides of the boat, and the addition of a non-waterproof top to the boat.

The sensing elements were flexures to which bonded semi-conductor strain-gage bridges were attached. Three flexures were necessary to measure all six components of forces and moments. Flexure 1 measured F_X and M_Y, Flexure 2 measured F_Y and M_X, and Flexure 3 measured F_Z and M_Z; see Figure 1. The flexures were mounted

inside a propeller hub specifically designed for these experiments. Only one flexure could be mounted at a time because of space limitations, and this necessitated three duplicate runs for each condition. The flexure calibration procedure was identical to that described in References 2 and 3.

Wake Screen and Wake Survey

A 16-inch (0.405 m) diameter wake screen designed to produce a dominant first harmonic of the circumferential variation of the axial velocity, was used in the experiments. This screen consisted of simply a base screen with one overlay screen and no support members in the region through which flow is drawn into the propeller disk.

Wakes were measured for three different flow regimes:
1. Shaft inclination ψ = 10 deg with no wake screen,
2. ψ = 20 deg with no wake screen,
3. ψ = 0 deg with the wake screen.

Figure 3 shows the velocity component ratios at the radial position near r=0.7R at which the various wake surveys were conducted. The circumferential variations of the velocity component ratios in the axial, tangential, and radial directions contained primarily first harmonic components.
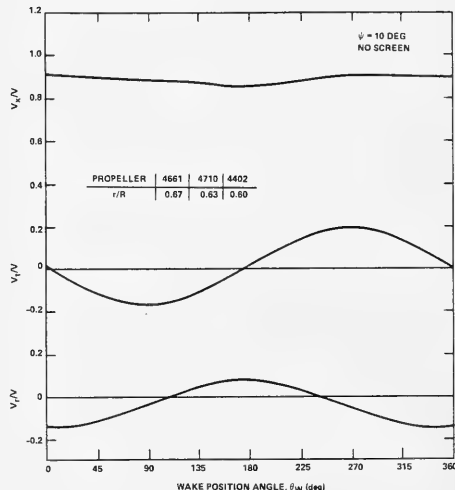
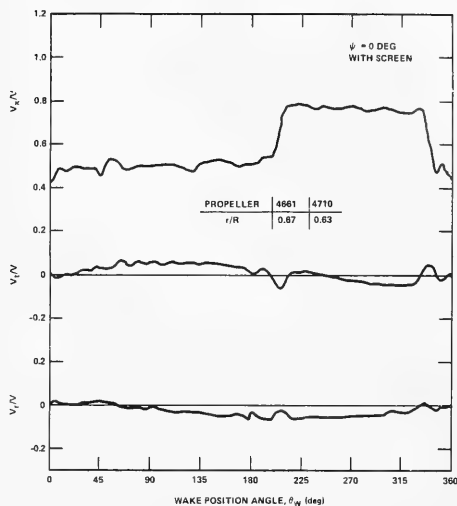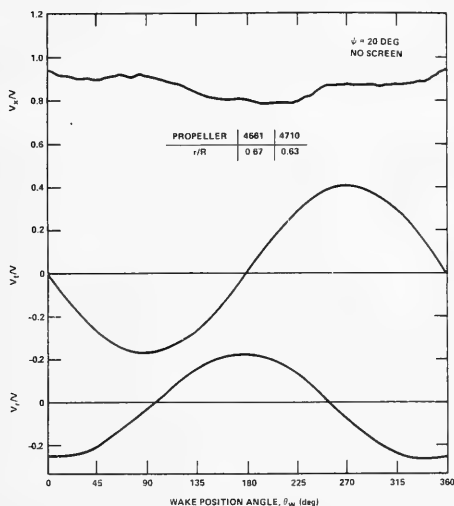Fig. 3 – Distribution of Wakes in Propeller Disks

Fig. 3 — (Continued)

Figure 3 shows that the variation of the longitudinal velocity component ratio V_x/V behind the wake screen is approximately a step function, as was expected. However, the high velocity region covers a smaller portion of the propeller disk than the low velocity region, whereas it was anticipated that the two velocity regions would each cover essentially half of the disk. This suggests that there is some cross flow between the propeller and the screen. This non-symmetry of the wake profile causes no problem regarding the objectives of the present investigation since it remains the same for all experimental conditions.

Experimental Conditions and Procedures

The propeller was located approximately 16 in (0.41 m) downstream of the screen for all conditions for which the screen was used. A 4.0 ft by 2.0 ft by 0.375 in (1.22 m by 0.61 m by 9.5 mm) plate was positioned parallel to the flow above the propeller for all experimental conditions. For Propeller 4402 at 10 degrees inclination, the plate clearance from the tip of the propeller was varied from 1.0 in (0.025 m) to 20 in (0.51 m). For all other conditions the plate clearance was approximately 20 in (0.51 m). With this clearance, the plate was 2 in (0.051 m) below the water surface. The plate at this location was used to minimize any possible effects of the free surface on the propeller performance.

The experimental conditions are as follows:
1. No Wake Screen, ψ = 10 deg, Propellers 4661, 4710, and 4402.
2. No Wake Screen, ψ = 20 deg, Propellers 4661, and 4710.
3. Wake Screen, ψ = 0 deg, Propellers 4661 and 4710.
4. No Wake Screen, ψ = 30 deg, Propeller 4661.

For each condition, the carriage speed was held constant and propeller rotation speed, n, was varied to obtain the desired range of advance coefficient, J. For each condition, the carriage speed for the blade loading measurements was the same as the carriage speed for the corresponding wake survey.

The first three conditions represent the more important types of experiments performed. The wake surveys were conducted at these conditions. The fourth condition was run to obtain limited data at a very large value of ψ so that the variation of loads with ψ could be better defined. Due to limited time, however, only the F_x and M_y components were measured on Propeller 4661, and no measurements were made on Propeller 4710. In addition, no wake survey was conducted at this condition due to limitations of the wake survey apparatus.

For each of these conditions, experiments were conducted over a range of advance coefficient J. For each

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condition, between 20 and 40 values of advance coefficient were evaluated in order to well define the manner in which the loading varies with advance coefficient. In general, each experimental condition was run three times, once for each of the three flexures. This was necessary in order to obtain all six components of force and moment. Data were also collected with the propellers rotating in air at 0, 10, 20, and 30 degrees of shaft inclination over the range of rotational speeds evaluated in water. This provided the gravitational and centrifugal loads that were later subtracted from the total propeller blade loads measured in water.

Data Acquisition and Analysis

Data were collected and analyzed in the same manner as in the steady ahead runs described in References 1 through 4. For each flexure, an Interdata 70 Computer was used to collect and average the force and moment data for each 4-degree increment of blade angular position over 200 to 300 propeller revolutions. Propeller rotation speed, n, and model (or carriage) velocity, V, were recorded for every set of two propeller revolutions, and averaged over the period during which data were collected.

At the end of each run, the computer analyzed and printed the data. The average force and moment signals for each 4-degree angular position were printed along with the average model velocity and propeller rotation speed for the run. The standard deviation of the accumulated data for the run was also calculated for V, n, and the force and moment signals at each position. A harmonic analysis was performed on the force and moment data providing the mean signal and amplitude and phase of the first 16 harmonics.

First, the experimental agenda was completed for all three flexures at each major condition (each propeller, wake screen, and value of ψ) except $\psi = 30$ deg. Then the corrections for interactions were calculated at five values of J at which measurements with all three flexures were made using the same procedures outlined in Reference 1 through 4. After the correction for interactions, the centrifugal and gravitational loads were subtracted from the total experimental loads to obtain the hydrodynamic loads.

Accuracy

The accuracy of the experiment was generally similar to that of the steady ahead runs in References 1 through 4. During a single run, where signals were averaged over many revolutions, the standard deviation of the measured forces and moments maintained a similar error (95 percent confidence band) of ± 5 to ± 10 percent of the averaged signal at each angular position. For a given run the average error in model speed V was approximately ± 1.0 percent, and the error in rotational speed n was less than ± 0.01 percent

Except for the fluctuations in signals occurring in a given run, the accuracy of the data is indicated by the repeatability of an identical condition. An effort was made to set experimental conditions identically on repeat runs; however, some variation was unavoidable due to manual setting of the model speed and propeller rotation speed, random zero shift in data channels, and minor variations in basin water conditions. This resulting error is approximately ± 2 percent of the measured first harmonic loading component. A more detailed error analysis based on the repeatability of the hydrodynamic, centrifugal and gravitational loads will be presented in a future DTNSRDC Report.

EXPERIMENTAL RESULTS

Loading Components

The basic loading components are shown in Figure 1. For a right-hand propeller the sign convention follows the conventional right-hand rule with right-hand Cartesian coordinate system. For a left-hand propeller all the loads are the same, but for this case the sign convention follows a left-hand rule with a left-hand Cartesian coordinate system.

Each component of loading is generally represented as a variation of the instantaneous values with blade angular position, θ, and as a Fourier series in blade angular position in the following form:

$$F, M(\theta) = (\overline{F}, \overline{M}) + \sum_{n=1}^{N} (F, M)_n \cos\left\{ n\theta - (\phi_{F,M})_n \right\} \quad (1)$$

In general, the loads consist of hydrodynamic, centrifugal and gravitational components. However, in this
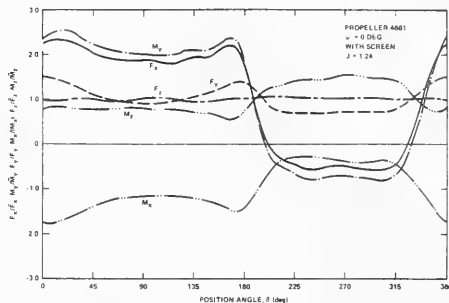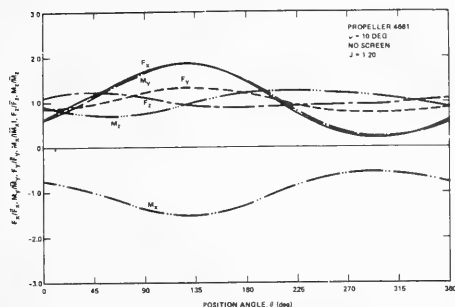
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Fig. 4 — Experimental Variation of Loading Components with Blade Angular Position

paper only the hydrodynamic component of blade loading is presented. Centrifugal and gravitational loads were measured soley to permit the hydrodynamic loads to be determined by subtracting the centrifugal and gravitational loads from the total experimental loads.

Centrifugal and Gravitational Loads

Centrifugal and gravitational loads were determined from air-spin experiments with each flexure over a range of rotational speed n for ψ = 0, 10, 20, and 30 deg. The centrifugal load, which is a time-average load in a coordinate system rotating with the propeller, should vary as n^2 and be independent of ψ. The time-average experimental data followed these trends closely. The gravitational load, which is a first harmonic load in a coordinate system rotating with the propeller, should vary with ψ and be independent of n. The first harmonic experimental data followed these trends closely.

The centrifugal and gravitational loads measured during these experiments agreed with the values previously reported in References 3 and 4 and the gravitational loads agreed with values deduced from the weights of the blades and associated flexures. Therefore, these results will not be repeated here.

Variation of Loads with Angular Position

Figure 4 shows the variations of the loading components with blade angular position for Propeller 4661 for operation with 10 degrees shaft inclination with no screen and for operation behind the wake screen with no shaft inclination. These plots present typical results obtained in inclined flow and behind the wake screen. For other conditions evaluated in inclined flow and behind the wake screen the trends are basically the same as shown in Figure 4, but the magnitude of the

unsteady loading varies with experimental conditions.

The variations of the primary load components, F_x and M_y with blade angular position in inclined flow and behind the wake screen follow patterns approximately similar to the tangential and the longitudinal velocity profiles of the respective wakes shown in Figure 3. The variation of the loads behind the wake screen implies that the high velocity region covers a smaller portion of the propeller disk than the low velocity region, which agrees with the measured wake data.

Effect of Plate Clearance

Figure 5 shows that the periodic blade loads in inclined flow are fairly insensitive to the presence of a nearby flat boundary parallel to the flow for tip clearance to propeller diameter (tip clearance ratio) as small as 0.1. The ratios of the periodic to the time-average loading components at tip clearance ratio of 0.1 are no greater than 10 percent larger than the
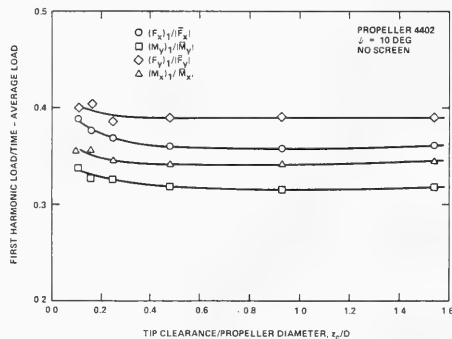

Fig. 5 — Effect of Plate Clearance on First Harmonic Loading in Tangential Wake
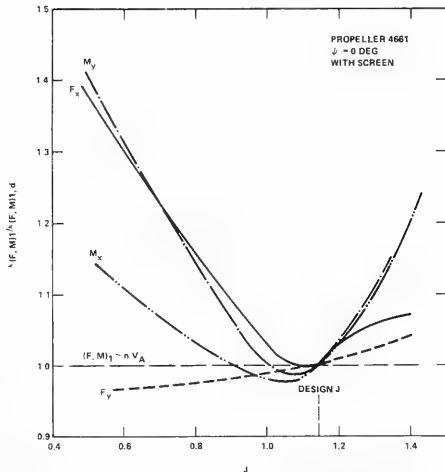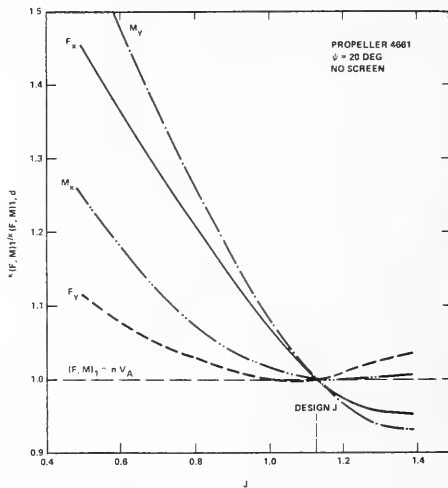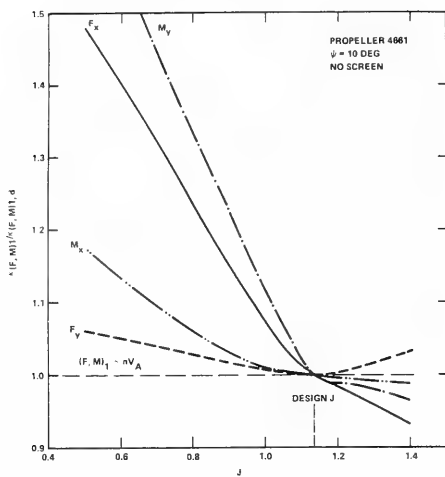
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Fig. 6 — Experimental Variation of First Harmonic Blade Loads
On Propeller 4661 with Advance Coefficient

corresponding values at very large tip
clearance ratios for Propeller 4402 with
an inclination angle ψ of 10 degrees.

Effect of Advance Coefficient

Figure 6 presents the trends of the
variations of the first harmonics of the
primary load components F_x, M_y,
F_y, and M_x with J for Propeller 4661
at the three primary experimental
conditions described in the section on
Experimental Conditions and Procedures.

In Figure 6 the force and moment
components are nondimensionalized as
follows:

$$\kappa_{(Fx,y)1} = \frac{(F_{x,y})_1}{\rho n V_A D^3} \qquad (2)$$

$$\kappa_{(Mx,y)1} = \frac{(M_{x,y})_1}{\rho n V_A D^4} \qquad (3)$$

where the subscript 1 represents the
first harmonic component, and V_A =
$V(1-w_{VM})$ is the speed of advance based
on the volume mean wake. This form of
nondimensionalization was used in part
to verify Wereldsma's argument (12) that
for a given propeller in a given wake
pattern the circumferential variation of
the hydrodynamic loading varies
approximately as nV_A; i.e., for a
given value of nV_A the circum-
ferential variation of hydrodynamic
loading is insensitive to J. This form
of nondimensionalization is different
only by a factor of the advance coeffi-
cient, J_A, from the conventional form
of nondimensionalization; i.e.,
$F_{x,y}/\rho n^2 D^4$ and $M_{x,y}/\rho n^2 D^5$.
The coefficients $\kappa_{(Fx,y)1}$
and $\kappa_{(Mx,y)1}$ in Figure 6 are all
normalized by the respective
coefficients at design J to illustrate
the relative sensitivity of the loading
coefficients to J, for different wakes.

The results presented in Figure 6
show that in tangential flow $\kappa_{(Fx,y)1}$
and $\kappa_{(Mx,y)1}$ generally decreases with

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increasing J. $\kappa_{(My)1}$ is the most sensitive to J, and $\kappa_{(Fy)1}$ is the least sensitive to J. Except for the F_y component, these data do not closely follow the trends indicated by Wereldsma (12). For the longitudinal wakes behind the screen, the slopes of $\kappa_{(F,M)}$ with increasing J are less negative than in inclined flow. The relative slopes among the four components are generally the same for each propeller-wake combination, except for some cases at greater than design J.

Figure 7 compares the variations of $\kappa_{(Fx)1}$ with J obtained in the present experiment in inclined flow with variations obtained in previous experiments in which the unsteady blade loads were determined over a range of J in inclined flow (13,14,15,16). Each of these sets of experimental results show that $\kappa_{(Fx)1}$ decreases substantially with increasing J.

Figure 8 compares the variation in $\kappa_{(Fx)1}$ with J obtained in the present experiment behind the wake screen with the blade frequency $\kappa_{(Fx)n}$ obtained in previous experiments in

which the unsteady bearing forces were measured in longitudinal wakes produced by screens in a closed-jet water tunnel (17,18,19). The results in References 17, 18, and 19 are for the blade frequency component of κ_{Fx}, whereas in the present investigation the shaft frequency component of κ_{Fx} was measured. However, the mechanism for generating the unsteady blade loading in axial flow appears to be independent of the harmonic of shaft rotation. Each of the three previous sets of experiments shows that $\kappa_{(Fx)n}$ decreases with increasing J to some minimum value near design J, and then increases with further increase in J. Figure 8 illustrates that variations of $\kappa_{(Fx)1}$ with J obtained in the present experiment generally follow the trend of the data in References 17, 18 and 19. In general, $\kappa_{(Fx)n}$ is somewhat less sensitive to J in longitudinal wake patterns than it is in tangential wake patterns.
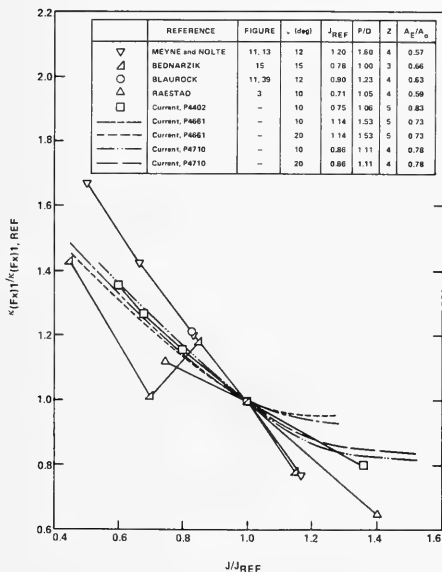

	REFERENCE	FIGURE	α (deg)	J_{REF}	P/D	Z	A_E/A_o
▽	MEYNE and NOLTE	11, 13	12	1.20	1.60	4	0.57
◁	BEDNARZIK	15	15	0.78	1.00	3	0.66
○	BLAUROCK	11, 39	12	0.90	1.23	4	0.63
△	RAESTAD	3	10	0.71	1.05	4	0.59
□	Current, P4402	–	10	0.75	1.06	5	0.83
——	Current, P4661	–	10	1.14	1.53	5	0.73
– – –	Current, P4661	–	20	1.14	1.53	5	0.73
—·—	Current, P4710	–	10	0.86	1.11	4	0.78
—·· —	Current, P4710	–	20	0.86	1.11	4	0.78

Fig. 7 – Comparison of First Harmonic Blade
Loading Coefficients in Tangential Wakes

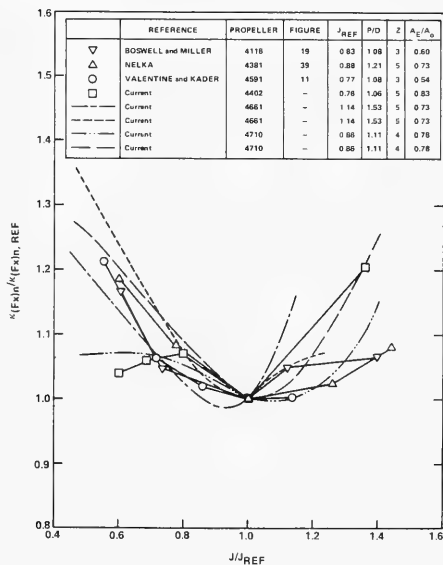|	REFERENCE	PROPELLER	FIGURE	J_{REF}	P/D	Z	A_E/A_o
▽	BOSWELL and MILLER	4118	19	0.83	1.08	3	0.60
△	NELKA	4381	39	0.88	1.21	5	0.73
○	VALENTINE and KADER	4591	11	0.77	1.08	3	0.54
□	Current	4402	–	0.78	1.06	5	0.83
——	Current	4661	–	1.14	1.53	5	0.73
– – –	Current	4661	–	1.14	1.53	5	0.73
—·—	Current	4710	–	0.86	1.11	4	0.78
—·· —	Current	4710	–	0.86	1.11	4	0.78

Fig. 8 – Comparison of Various Experimental Blade
Loading Coefficients in Longitudinal Wakes

CORRELATION BETWEEN EXPERIMENTAL RESULTS
AND THEORETICAL PREDICTIONS

Theoretical Methods

The experimental results were
correlated with predictions based on the
following methods:
1. The quasi-steady method developed
   at DTNSRDC by McCarthy (5);
   Computer Program QUASI.
2. The procedure developed at Davidson
   Laboratory by Tsakonas, et al (6,7)
   based on lightly-loaded unsteady
   lifting surface theory;   Computer
   Program PPEXACT.
3. The procedure developed at MIT by
   Kerwin and Lee (8) based on
   moderately-loaded unsteady lifting
   surface theory; Computer Program
   PUF2.
4. A refinement of the method of
   Kerwin and Lee (8) developed at MIT
   by Kerwin (9), to allow the axis of
   the propeller slipstream to depart
   from the propeller axis for opera-
   tion in inclined flow; Computer
   Program PUF2IS.

The procedure developed by McCarthy
(5) is a simple quasi-steady procedure
utilizing the open water characteristics
of the propeller. It is assumed that
the thrust and torque developed by the
propeller blade at any angular position
in a circumferentially nonuniform wake
is the same as would be produced by the
propeller blade if it were operating
continuously at the advance coefficient
J and rotational speed n based on the
local wake at the angular position
corresponding to the mid-chord of the 70
percent radius. It is further assumed
that the instantaneous thrust and torque
can be adequately estimated by entering
the propeller open water characteristics
at the values of J and n based on a
weighted average over the propeller
radius of the wake at the local blade
angular position. This simple method
can be expected to yield reasonable
results only if the reduced frequency of
interest is low, the propeller projected
skew is small relative to the wave
length of the pertinent wake harmonic,
and the wake harmonic corresponding to
the force harmonics of interest does not
vary substantially in amplitude or phase
with radius. These conditions are met
for propellers and wakes being evaluated
in the present paper.

The procedure developed by
Tsakonas, et al (6,7), is based on the
linearized unsteady lifting surface
theory for a lightly-loaded propeller
using an acceleration potential. The
numerical procedure applies the mode
approach and collocation method in
conjunction with the "generalized lift
operator" technique. This procedure
based on the frequency domain assumes
that a given harmonic of blade loading
depends upon the corresponding harmonic
of the wake velocity normal to the blade
chord line, independent of whether the
normal velocity results from axial or
tangential components of the wake.
The blade load does not depend upon the
radial variation of the circumferential
mean wake. The shed and trailing
vortices are assumed to lie on an
"exact" helicoidal surface of constant
pitch extending to downstream infinity
determined by the propeller rotational
speed and a single axial inflow
velocity. The axis of this helicoidal
surface coincides with the propeller
axis, regardless of the inclination of
the propeller shaft to the incoming
flow. This method does not consider the
contraction or roll-up of the propeller
slipstream. All geometric characteris-
tics of the propeller are considered,
except rake, camber, and thickness which
are assumed to be zero.

Valentine (20) developed a
refinement to the method of Tsakonas, et
al (6,7) for operation in slightly
inclined flow. This refinement, in
effect, replaces the "exact" helicoidal
wake whose axis coincides with the
propeller axis with a slightly distorted
one in the direction of the inflow
velocity. The refinement, which is
incorporated as a perturbation for small
inclination angles, relates the unknown
loading at the first harmonic of shaft
frequency with the loadings at the mean
and second harmonics of shaft frequency
evaluated without the distorted helicoi-
dal wake. All other assumptions of the
method of Tsakonas et al, are retained.

Calculations made by Valentine (20)
showed that his modification to the
method of Tsakonas et al, did not
significantly improve the poor
correlation between this method and
experimental blade loads in inclined
flow. Further, with the modifications
by Valentine the disagreement in phase
between predicted and experimental blade
loads in inclined flow were even worse
than the agreement obtained with the
method of Tsakonas et al. Valentine
concluded that the effects of shaft
inclination required a moderately-loaded
propeller theory, and could not be
adequately calculated based on the
lightly-loaded formulation of Tsakonas
et al. Therefore, the theory of
Tsakonas et al, as modified by Valentine
was not correlated with the experimental
results in the present paper.

The numerical method developed by Kerwin and Lee (8) is based on a linearized lifting-surface theory in the time domain. The propeller blades are represented by a spanwise and chordwise distribution of discrete line vortex and source elements located on the exact camber surface of the blade. Thus the geometric complications of skew, rake and radial variation in pitch are readily accommodated. The trailing vortex wake is permitted to contract and roll up, and the effect of vortex sheet separation from the blade tip is taken into consideration. The inflow velocity to the propeller may have radially and circumferentially varying axial, tangential, and radial components, and may therefore give rise to both steady and unsteady blade loading. This method, like the method of Tsakonas et al, assumes that the axis of the propeller slipstream coincides with the propeller axis.

Kerwin (9) developed a refinement to the method of Kerwin and Lee (8) for operation in inclined flow where the slipstream is not axisymmetric about the propeller shaft. This refinement entails a more realistic representation of the path of the propeller slipstream. In this method the axis of the slipstream coincides with the propeller axis immediately behind the propeller, and coincides with the direction of the mean inflow far downstream in the ultimate wake. A simple function is assumed for the slipstream axis in the wake region between the propeller and the ultimate wake. Due to the asymmetry, the position of the trailing vortex wake relative to a blade oscillates with a once-per-revolution fundamental frequency, thus giving rise to unsteady induced velocities normal to the blade surface and thereby unsteady blade loadings of the same frequency. The strength of the vorticity in the wake, and thus the induced once-per-revolution variation of loading on the blades, is dependent upon the time-average loading of the propeller. All other characteristics of the method of Kerwin and Lee except for roll-up are retained, including the flexibility for the trailing vortex wake to contract, and allowance for the effect of vortex sheet separation from the blade tip.

Correlations in Tangential Wakes

Figures 9 and 10 present the amplitudes and phases, respectively, of the first harmonic loads on Propellers 4661, 4710, and 4402 operating in the various tangential wakes over a range of

advance coefficient J. These figures present both experimental results and predictions based on the various theoretical methods described in the preceding section. For Propeller 4661 with 10 degrees shaft inclination, the first harmonic components of F_x, M_y, F_y, and M_x are presented. For other conditions only the F_x component is shown. The results in Figure 9 and 10 are summarized in Table II for design J.

In the tangential wakes, a consistent variation from the experimental data occurred in the theoretical predictions for the three propellers evaluated. With few isolated exceptions, all of the theoretical methods underpredicted all of the loading components throughout the range of conditions evaluated. In general, the correlations are better for the F_x and M_y components than for the F_y and M_x components. The F_x and M_y components are the more important components since, in general, these are larger than the F_y and M_x components.

The quasi-steady method of McCarthy (5) underpredicted the amplitude of $(F_x)_1$ by approximately 10 to 30 percent of the experimental values with closer agreement at higher values of J. The quasi-steady predictions maintained a similar trend to the experimental data for F_x and M_x components for all conditions in tangential wakes; i.e., both the experimental and predicted values of $^\kappa(F_x)_1$ and $^\kappa(M_x)_1$ decrease with increasing J. For a given propeller the predicted slope of the $^\kappa(F_x)_1$ and $^\kappa(M_x)_1$ curves (not shown) with J increases with increasing amplitude of the tangential wake. No predictions of $(F_y)_1$ and $(M_y)_1$ were made with the quasi-steady procedure since this method does not predict the radial center of the load. These components could be predicted by the quasi-steady method by assuming a radial position of application of the load.

The phases presented in Figure 10 show that the quasi-steady method of McCarthy predicts that the maximum values of the loading components will occur at approximately 10 to 20 degrees of blade angular position before the experimentally determined angles.

Predictions by the unsteady theory of Tsakonas et al (6,7) did not agree well with experimental results in tangential flow. This theory predicts that the amplitudes of all four loading coefficients increase with increasing J,
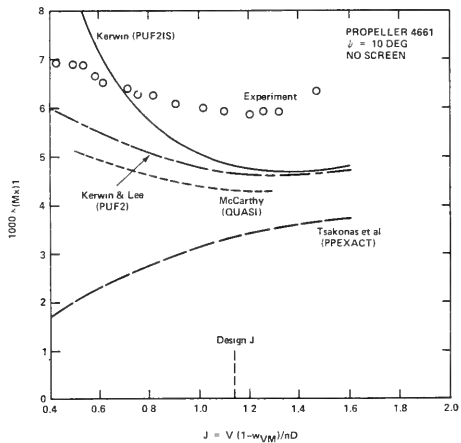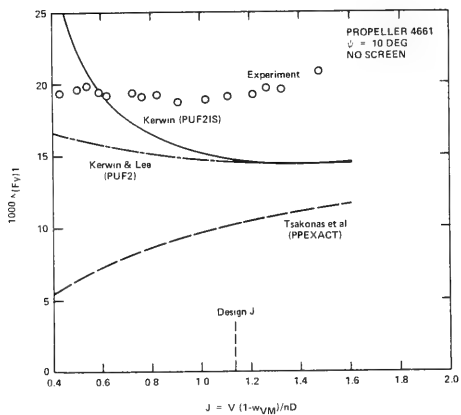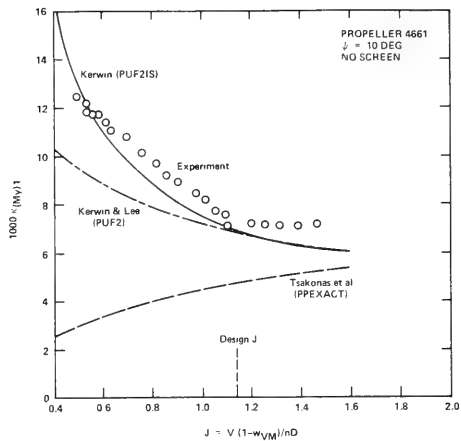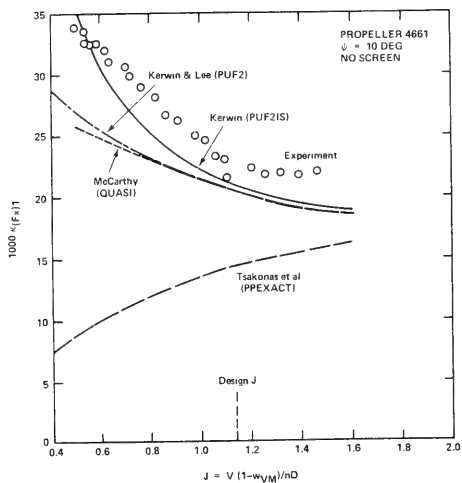
Fig. 9 — Amplitudes of First Harmonic Blade Loads in Tangential Wakes; Correlation Between Experiment and Theory

Fig. 9 — (Continued)

13

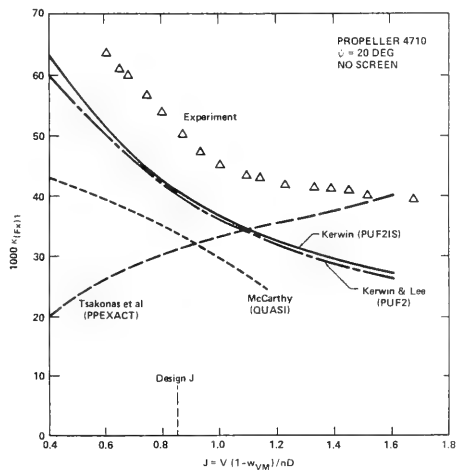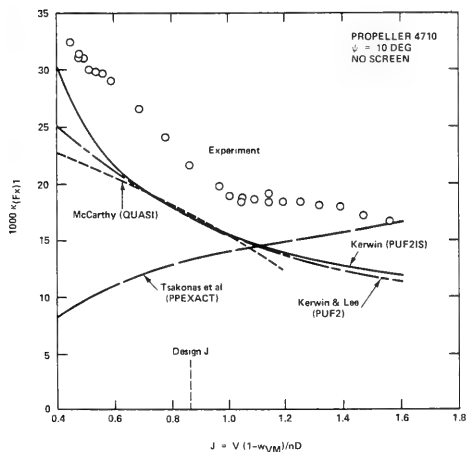Fig. 9 — (Continued)

Fig. 10 — Phases of First Harmonic Blade Loads in Tangential Wakes
Correlation Between Experiment and Theory
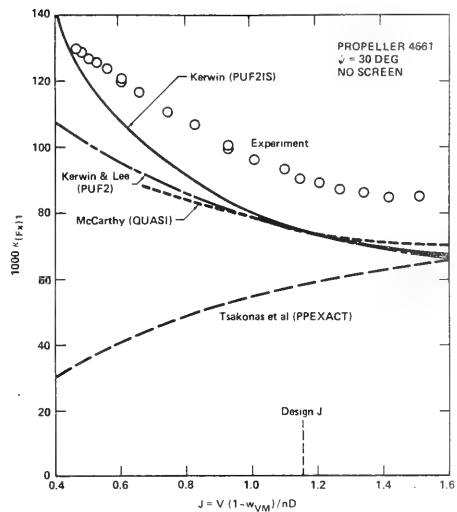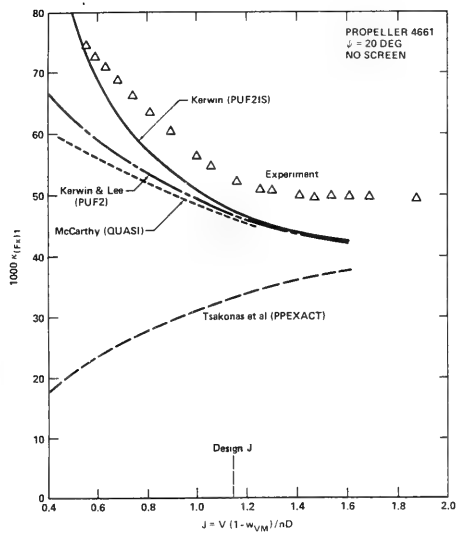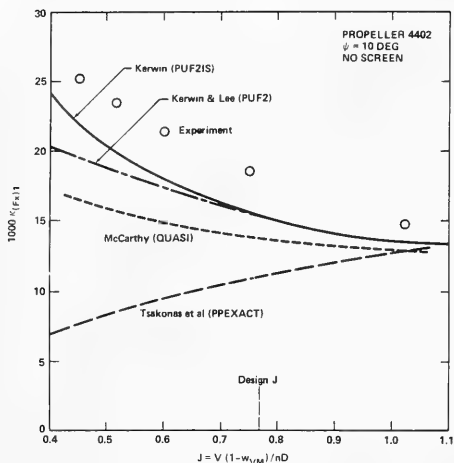
which is opposite to the trend of the experimental data. Since this is a lightly-loaded linear theory, it was anticipated that the predicted unsteady loading coefficients $\kappa_{(F,M)1}$, would be essentially independent of J. An earlier version of the unsteady lifting surface method developed by Tsakonas and his associates (21) at Davidson Laboratory, in which the propeller helical wake was approximated in a staircase manner did predict that the periodic loading coefficients $\kappa_{(F,M)}$ in axial wakes were essentially independent of J (17). It is not clear why the method of Tsakonas et al (6,7) predicts that $\kappa_{(F,M)1}$ increases substantially with increasing J.

In general, the predictions by the method of Tsakonas et al are closer to the experimental results at high advance coefficients than they are at low advance coefficients. The predicted amplitudes are approximately 65 percent of the experimental value at design J and 30 to 35 percent of the experimental values at the lowest values of J evaluated. The finding that this method predicts periodic loads in inclined flow that are significantly less than the experimental values is consistent with the results presented in References 1 through 4.
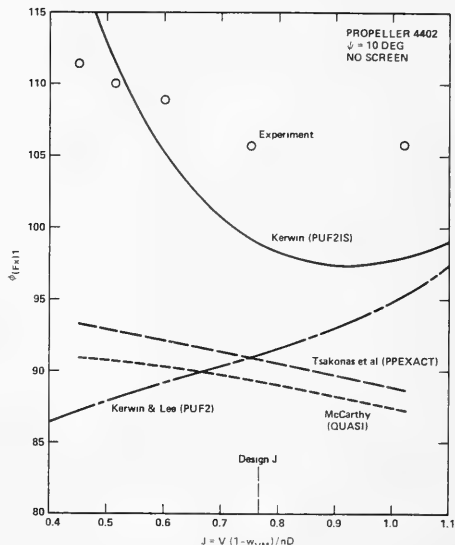
The unsteady theory of Tsakonas et al predicts that the maximum values of the loading components will occur at approximately 15 to 20 degrees of blade angular position before the experimentally determined angles; see Figure 10.

The unsteady theory of Kerwin and Lee (8) showed, in general, somewhat better agreement with experimental data over a range of advance coefficient than either the quasi-steady method of McCarthy or the unsteady method of Tsakonas et al. This applies to both amplitudes and phases. The trends of the predictions of the amplitudes over a range of advance coefficients were very similiar to the trends of the predictions by the method of McCarthy. The method of Kerwin and Lee underpredicted the periodic loads, by approximately 5 to 20 percent of the experimental values, with closer agreement being obtained for the F_x and M_y components at the higher values of J.

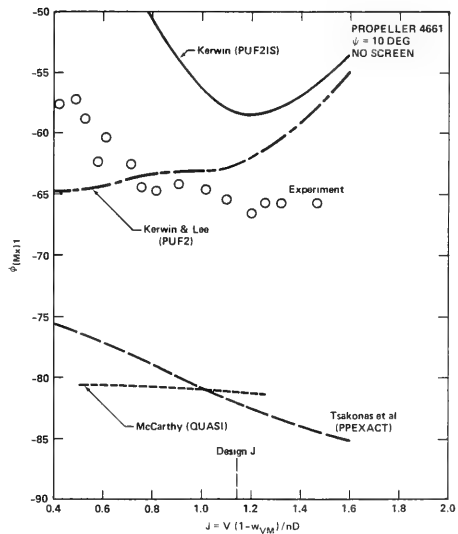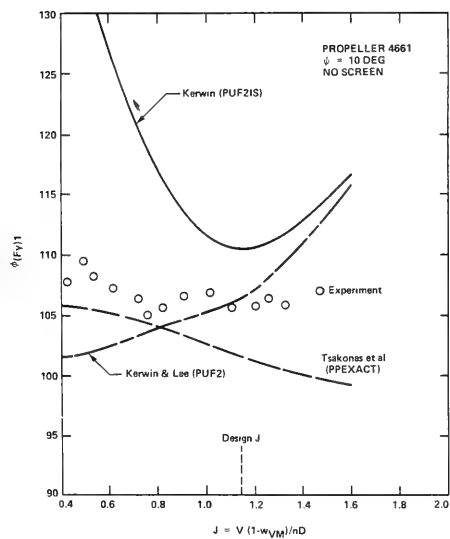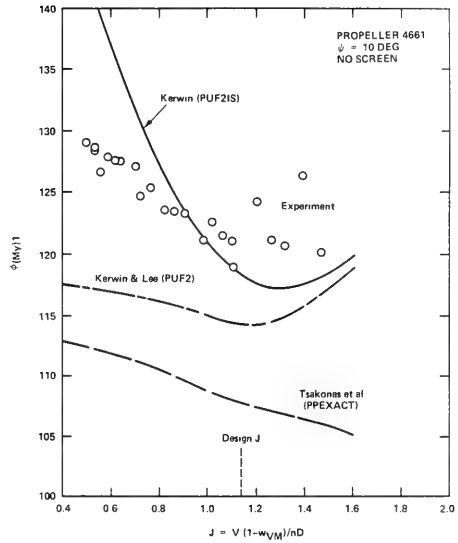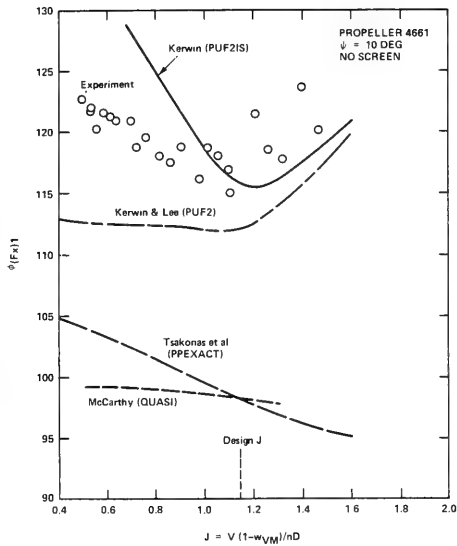The unsteady theory of Kerwin and Lee predicts the phases to within 5 to 15 degrees of the experimental values
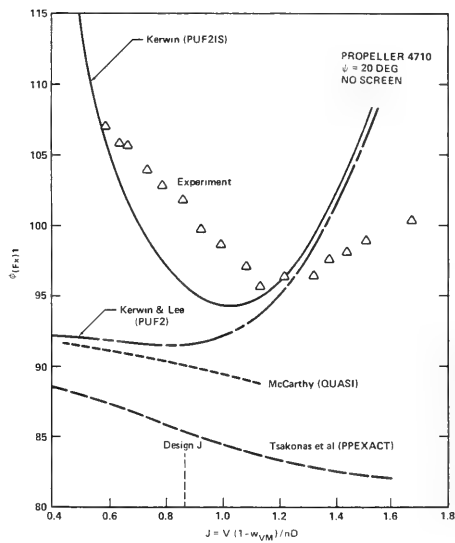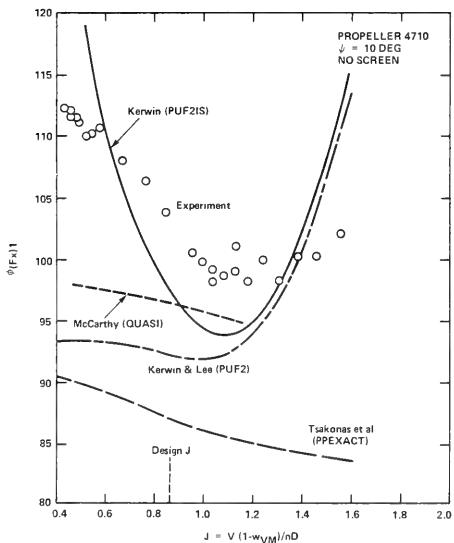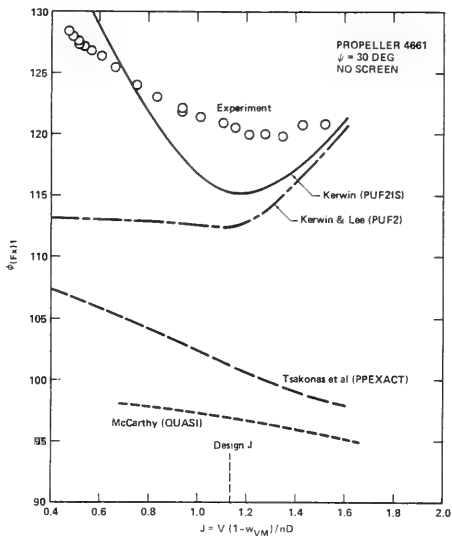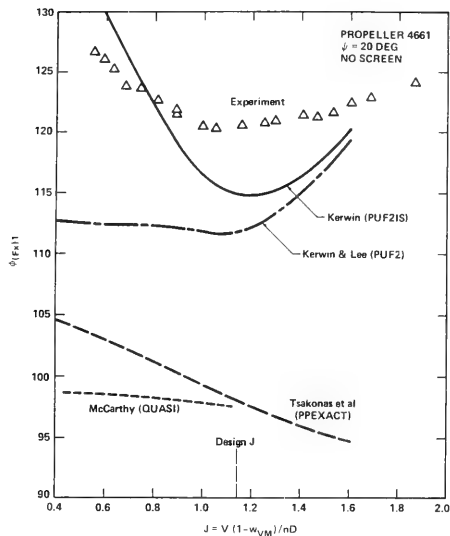
14

Fig. 10 — (Continued)

15

Fig. 10 — (Continued)

16

PROPELLER 4661, ψ = 10 DEG, J = 1.14

AMPLITUDE	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$	$1000 \cdot K_{(My)1}$	$\dfrac{K_{(My)1}}{K_{(My)1,\,EXP}}$	$1000 \cdot K_{(Fy)1}$	$\dfrac{K_{(Fy)1}}{K_{(Fy)1,\,EXP}}$	$1000 \cdot K_{(Mx)1}$	$\dfrac{K_{(Mx)1}}{K_{(Mx)1,\,EXP}}$
Experiment	23.00		7.50		19.10		5.90	
McCarthy (QUASI)	20.50	0.89	—	—	—	—	4.31	0.73
Tsakonas et al (PPEXACT)	14.50	0.63	4.80	0.64	10.36	0.54	3.34	0.57
Kerwin and Lee (PUF2)	20.35	0.88	6.75	0.90	14.47	0.76	4.65	0.79
Kerwin (PUF2IS)	20.79	0.90	6.93	0.92	14.74	0.78	4.82	0.82

PHASE ANGLE	$\phi_{(Fx)1}^{*}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$	$\phi_{(My)1}$	$\phi_{(My)1} - \phi_{(My)1,\,EXP}$	$\phi_{(Fy)1}$	$\phi_{(Fy)1} - \phi_{(Fy)1,\,EXP}$	$\phi_{(Mx)1}$	$\phi_{(Mx)1} - \phi_{(Mx)1,\,EXP}$
Experiment	117.0		120.4		106.0		−65.8	
McCarthy (QUASI)	98.3	−18.7	—	—	—	—	−81.2	−15.4
Tsakonas et al (PPEXACT)	98.2	−18.8	107.8	−12.6	101.8	−4.2	−82.0	−16.2
Kerwin and Lee (PUF2)	112.0	−5.0	114.2	−6.2	106.3	0.3	−62.8	3.0
Kerwin (PUF2IS)	115.7	−1.3	118.1	−2.3	110.3	3.7	−58.6	7.2

*All phase angles are in degrees.

CONDITION	PROPELLER 4661 ψ = 20 DEG		PROPELLER 4661 ψ = 30 DEG		PROPELLER 4710 ψ = 10 DEG		PROPELLER 4710 ψ = 20 DEG		PROPELLER 4402 ψ = 10 DEG	
AMPLITUDE	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$	$1000 \cdot K_{(Fx)1}$	$\dfrac{K_{(Fx)1}}{K_{(Fx)1,\,EXP}}$
Experiment	53.00		91.00		21.80		50.43		18.10	
McCarthy (QUASI)	46.20	0.87	75.00	0.82	17.30	0.79	33.70	0.67	13.70	0.76
Tsakonas et al (PPEXACT)	33.33	0.63	58.30	0.64	13.30	0.61	31.55	0.63	11.00	0.61
Kerwin and Lee (PUF2)	46.58	0.88	74.47	0.82	17.10	0.78	39.92	0.79	15.45	0.85
Kerwin (PUF2IS)	47.28	0.89	75.44	0.83	17.10	0.78	40.20	0.80	15.47	0.85

PHASE ANGLE	$\phi_{(Fx)1}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$	$\phi_{(Fx)1}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$	$\phi_{(Fx)1}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$	$\phi_{(Fx)1}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$	$\phi_{(Fx)1}$	$\phi_{(Fx)1} - \phi_{(Fx)1,\,EXP}$
Experiment	120.5		120.6		103.8		102.0		105.5	
McCarthy (QUASI)	97.5	−23.0	96.9	−23.7	96.5	−7.3	90.1	−11.9	89.2	−16.3
Tsakonas et al (PPEXACT)	98.1	−22.4	101.1	−19.5	87.2	−16.6	85.5	−16.5	90.8	−14.7
Kerwin and Lee (PUF2)	111.7	−8.8	112.4	−8.2	92.0	−11.8	91.5	−10.5	91.2	−14.3
Kerwin (PUF2IS)	114.8	−5.7	115.2	−5.4	97.7	−6.1	96.0	−6.0	98.8	−6.7

for most conditions evaluated. In general, the agreement is better for the higher values of advance coefficient J; i.e., J near or higher than the design value.

The method of Kerwin (9), which is a refinement to the method of Kerwin and Lee to account for the effect of the inclined slipstream, showed substantial improvement over the predictions of amplitudes and phases by the method of Kerwin and Lee at values of J which are substantially less than the design J. For higher J values, i.e., J near or higher than the design value, where the method of Kerwin and Lee was in closer agreement with experimental results, the improvement by the method of Kerwin was smaller. This implies that the influence of the non-axi-symmetric wake due to shaft inclination on the fluctuating forces becomes larger at lower values of advance coefficient. This trend is expected, as pointed out by Kerwin (9), since the effect of wake asymmetry is the combined result of the time-average loading and the oscillating position of the trailing vortex wake relative to a point fixed on the blade. At low advance coefficients, the mean loading is higher, and the pitch of the trailing vortex wake is smaller. This smaller pitch of the propeller wake tends to increase the influence of the fluctuating wake position relative to the blade on induced velocities since the downstream wake is closer to the propeller blades.

In summary, these correlations show that the inclination of the propeller slipstream relative to the propeller axis can significantly influence the periodic loads on the propeller blades. The importance of this inclination increases with increasing time-average loading. Of the four methods evaluated, the method of Kerwin, which accounts for the inclination of the slipstream, gives the best predictions of the amplitudes and phases of the periodic blade loads. The method of Tsakonas et al gives the worst prediction of the amplitudes of the periodic loads. Further, this method failed to predict the trend of the variation of the loading coefficients with advance coefficient.

Figure 11 presents the variation of the periodic loads with inclination angle for Propeller 4661 near design J. These results show that the rate of increase of the periodic loads with inclination angle increases with increasing inclination angle. Figure 11 also shows that the correlation between experimental resulsts and analytical

method of Kerwin, which considers the inclination of the propeller slipstream, is essentially independent of the angle of inclination up to 30 degrees.
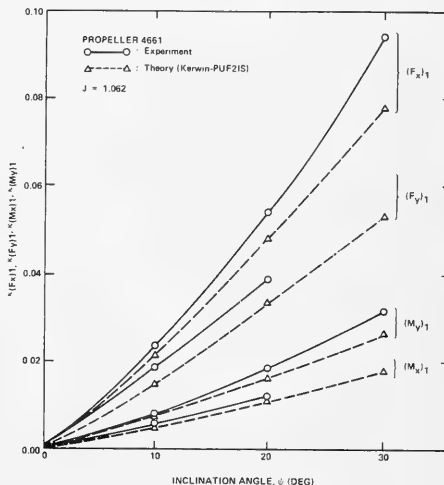
Fig. 11 — Variation of Periodic Blade Loads with Shaft Inclination

Correlations in Longitudinal Wakes

Figures 12 and 13 present the amplitudes and phases, respectively, of the first harmonic of the F_x component on Propellers 4661 and 4710 in the longitudinal wake patterns generated by the upstream wake screen over a range of advance coefficient J. The circumferential variation of the longitudinal component of the incoming velocity is essentially a once-per-revolution variation with low velocity on the left half of the propeller disk and high velocity on the right side of the propeller disk looking upstream; see Figure 3. Figures 12 and 13 also present the correlation between experimental results and predictions based on the three theoretical methods described previously.* The results in Figures 12 and 13 are summarized in Table III for design J.

*For longitudinal inflow where $\psi = 0$, the method of Kerwin (9) is identically the same as the method of Kerwin and Lee (8).

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Fig. 12 — Amplitudes of First Harmonic Blade Loads in Longitudinal Wakes; Correlation
Between Experiment and Theory

Fig. 13 — Phases of First Harmonic Blade Loads in Longitudinal Wakes; Correlation
Between Experiment and Theory

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TABLE III — COMPARISON OF EXPERIMENT AND THEORY IN
LONGITUDINAL FLOW — AMPLITUDES AND PHASES
OF FIRST HARMONIC LOADING COEFFICIENTS
AT DESIGN J

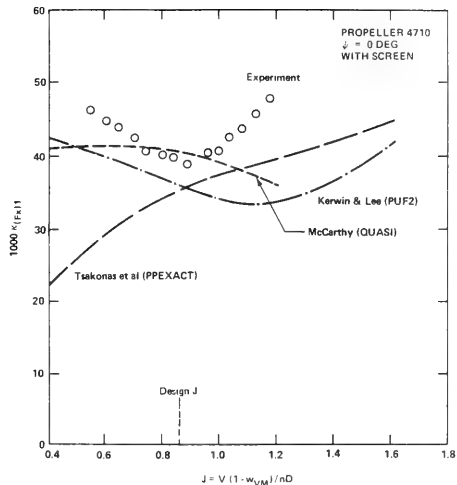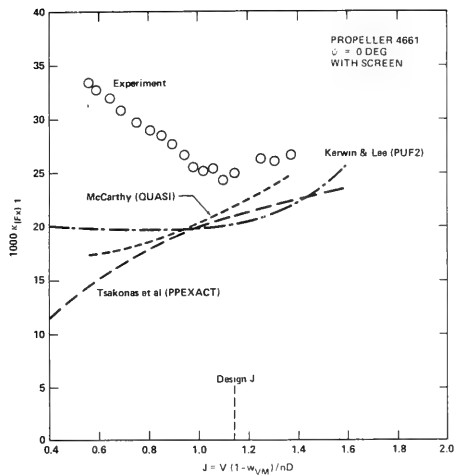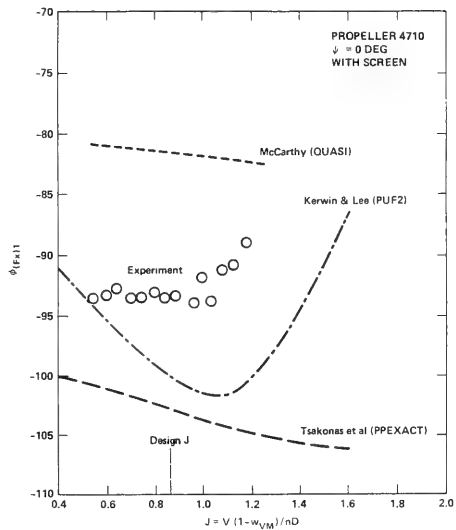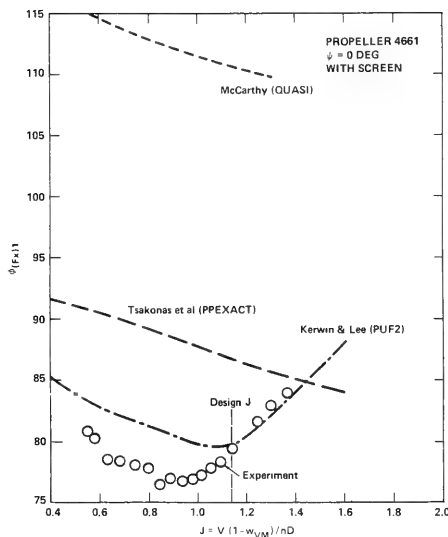| CONDITION	PROPELLER 4661 $\psi = 0$ DEG		PROPELLER 4710 $\psi = 0$ DEG	
AMPLITUDE	$1000 \cdot$ $\kappa_{(Fx)1}$	$\dfrac{\kappa_{(Fx)1}}{\kappa_{(Fx)1, EXP}}$	$1000 \cdot$ $\kappa_{(Fx)1}$	$\dfrac{\kappa_{(Fx)1}}{\kappa_{(Fx)1, EXP}}$
Experiment	24.92		39.60	
McCarthy (QUASI)	21.70	0.87	40.50	1.02
Tsakonas et al (PPEXACT)	21.00	0.84	35.50	0.90
Kerwin and Lee (PUF2)	19.91	0.80	36.00	0.91

PHASE ANGLE	$\phi_{(Fx)1}$	$\phi_{(Fx)1} -$ $\phi_{(Fx)1, EXP}$	$\phi_{(Fx)1}$	$\phi_{(Fx)1} -$ $\phi_{(Fx)1, EXP}$
Experiment	79.4		– 93.2	
McCarthy (QUASI)	110.6	31.2	– 81.6	11.6
Tsakonas et al (PPEXACT)	86.8	7.4	–102.7	–9.5
Kerwin and Lee (PUF2)	79.6	0.2	–100.0	–6.8

The experimental curve presenting $\kappa_{(Fx)1}$ versus advance coefficient J shows a concave shape with a minimum value near design J; see Figure 12. The same trend was observed for other loading components (not shown). All of the theoretical methods are in good agreement with experimental $\kappa_{(Fx)1}$ near design J; however, they did not, in general, agree well with experimental $\kappa_{(Fx)1}$ over a wide range of J. The correlations between experiments and theoretical predictions are somewhat different for the two propellers.

The predictions by the quasi-steady method of McCarthy showed different trends for different propellers. For Propeller 4661, the predicted values of and $\kappa_{(Fx)1}$ and $\partial\kappa/\partial J$ increase with increasing J. For Propeller 4710, however, the predicted values of $\kappa_{(Fx)1}$ and $\partial\kappa/\partial J$ decrease with increasing J. The trends of the predictions by the quasi-steady method of McCarthy are quite sensitive to small changes in the slopes of the open water curves; i.e. $\overline{K}_T$ versus J and $\overline{K}_Q$ versus J.

The phases shown in Figure 13 show that the quasi-steady method of McCarthy predicts that the maximum value of $(F_x)_1$, will occur at approximately

25 and 10 degrees of blade angular position after the experimentally determined angles for Propellers 4661 and 4710, respectively*.

The unsteady theory of Tsakonas et al (6,7) predicts a similar trend of $\kappa_{(Fx)1}$ with J in axial and tangential wakes; i.e., the predicted $\kappa_{(Fx)1}$ tends to increase with increasing J and $\partial\kappa/\partial J$ to decrease with increasing J. These predicted trends are similar because this method considers only the component of wake resolved normal to the blade pitch line, for either longitudinal or tangential wakes. Thus, as discussed previously, this method does not distinguish between longitudinal and tangential wakes.

The trend of $\kappa_{(Fx)1}$ with J predicted by the method of Tsakonas et al does not agree with the experimental results. At low values of J; i.e., high time-average loading coefficient, this method gives the worst correlation with experimental results among the three methods evaluated. This occurs, in part, because the theory does not account for the influence of the time-average loading. As discussed in the preceding section, it is unclear why this method predicts that the loading coefficient decreases with decreasing J, rather than predicting that it is insensitive to J.

Near design J, the method of Tsakonas et al (6,7) predicts $\kappa_{(Fx)1}$ in longitudinal wakes which is close to the predictions by the other calculation methods, and reasonably close to experimental results. In contrast, in inclined flow the method of Tsakonas et al predicts much smaller values of $\kappa_{(Fx)1}$ than either the other calculation methods or the experiments even at design J; see Figure 9. In particular, near design J the predictions of $\kappa_{(Fx)1}$ by Tsakonas et al agree with the predictions of Kerwin and Lee in longitudinal flow but not in inclined flow. This suggests that the tangential inflow velocities significantly influence the periodic blade loads in a manner which is considered by the method of Kerwin and Lee but which is not properly considered by the method of Tsakonas et al.

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*Recall that Propeller 4661 rotates left-hand and propeller 4710 rotates right-hand, and the phase angle is the angle of the blade reference line which the maximum positive loading occurs measured from the upward vertical positive in the direction of propeller rotation.

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The unsteady method of Tsakonas et al predicts that the maximum value of $(F_x)_1$ in the longitudinal wake will occur at approximately 10 degrees after the experimental value for Propeller 4661 and approximately 10 degrees before the experimental value for Propeller 4710; see Figure 13.

The variations of $\kappa_{(Fx)1}$ predicted by the method of Kerwin and Lee (8) agrees more closely with the experimental results than either of the other two methods evaluated. However, the agreement with experimental results is not as good as that obtained in inclined flow by the method of Kerwin.

The magnitude and the variation of the phases with advance coefficient predicted by the method of Kerwin and Lee agree with the experimental results substantially better than do those predicted by either of the other two predictions evaluated. Except for $J > 1.0$ on Propeller 4710, the phases predicted by Kerwin and Lee are within 5 degrees of the experimental phases.

In summary, all three of the calculation procedures predicted $\kappa_{(Fx)1}$ to within 20 percent of the experimental values at design J. However, the agreement at substantially off-design J was not as good. In general, the method of Kerwin and Lee gave the best agreement with experimental results in the magnitude and trend of $\kappa_{(Fx)1}$ over a range of J. In addition, the method of Kerwin and Lee gave the best agreement with experimental results in phases and in the trends of the variation of phases with J.

SUMMARY AND CONCLUSIONS

An investigation was undertaken to evaluate the periodic single-blade loads on propellers and the influence of a nearby solid boundary on the periodic blade loads in inclined flow and in circumferentially non-uniform longitudinal velocity fields. Systematic model experiments were conducted and the results were correlated with predictions by the following methods:

1. A simple quasi-steady procedure developed by McCarthy at DTNSRDC which utilizes the open water characteristics of the propeller.
2. A linearized lightly-loaded unsteady lifting surface theory developed by Tsakonas and his colleagues at Davidson Laboratory.
3. A moderately-loaded unsteady lifting surface theory developed by Kerwin and Lee at MIT.
4. A refinement by Kerwin to the method of Kerwin and Lee which considers the inclination of the propeller slipstream for operation in inclined flow.

The results are as follows:
1. In inclined flow, all four of the calculation methods evaluated consistently underpredicted the experimental values of the periodic propeller blade loads. The method of Kerwin, which considers the inclination of the slipstream relative to the propeller axis, produced the best correlation with experimental values, and the method of Tsakonas et al produced the worst correlation with experimental values. The correlation of each method evaluated is as follows:

a. The method of Tsakonas et al predicts the first harmonic loading to be approximately 35 percent of the experimental value at the lowest advance coefficient investigated, 65 percent of the experimental value at the design condition and 80 percent of the experimental value at the highest advance coefficient investigated. This method predicts a variation of first harmonic loading coefficients with advance coefficient which is substantially different from that obtained experimentally. This method predicts that the maximum values of loading will occur at approximately 15 to 20 degrees of blade angular position before the experimentally determined angle.

b. The quasi-steady method of McCarthy underestimates the first harmonic loading by 10 to 30 percent over a range of advance of coefficients with closer agreement at higher values of J. This method predicted a similar trend to the experimental data; i.e., that the loading coefficient decreases with increasing J. This method predicts that the maximum values of loading will occur at approximately 10 to 20 degrees before the experimentally determined angle.

c. The unsteady theory of Kerwin and Lee showed, in general, somewhat better agreement with experimental data over a range of advance coefficient than either the quasi-steady method of McCarthy or the unsteady method of Tsakonas et al. This applies to both amplitudes and phases. This method underpredicted the periodic loads by approximately 5 to 20 percent of the experimental values, with closer agreement being obtained for the F_x and M_y components at the higher values of J. This method predicts the phases to within 5 to 15 degrees of the experimental values for most, but not all, conditions evaluated. In general, the agreement is better for the higher values of advance coefficient J; i.e., J near or higher than the design value.

d. The method of Kerwin, which is the only method evaluated that considers the inclination of the slipstream relative to the propeller axis, produced consistently the best agreement with experimental data, including both amplitudes and phases over the range of parameters evaluated. In particular, for low values of J this method yielded substantially better correlation with experimental results than any of the other methods evaluated. At high values of advance coefficient this method yields substantially the same results as the method of Kerwin and Lee. Thus, the inclination of the propeller slipstream relative to the propeller axis can significantly influence the periodic propeller blade loads, and the importance of this inclination increases with increasing time-average loading.

2. In longitudinal flow, all of the calculation procedures evaluated predict the amplitude of the periodic single-blade axial force to within 20 percent of the experimental values at design J. However, the agreement at substantially off-design J is not as good. In general, the method of Kerwin and Lee agrees best with experimental results in the magnitude and the trend of periodic single-blade

axial force coefficient over a range of J. In addition, the method of Kerwin and Lee agrees the best with experimental phases and in the trends of the variation of phases with J.

3. The periodic blade loads in inclined flow are not significantly influenced by the presence of a nearby boundary.

ACKNOWLEDGEMENTS

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